

Development of the J-2X Engine for the Ares I Crew Launch Vehicle and the Ares V Cargo Launch Vehicle: Building on the Apollo Program for Lunar Return Missions

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Abstract

The United States (U.S.) Vision for Space Exploration directs NASA to develop two new launch vehicles for sending humans to the Moon, Mars, and beyond. In January 2006, NASA streamlined its hardware development approach for replacing the Space Shuttle after it is retired in 2010. Benefits of this approach include reduced programmatic and technical risks and the potential to return to the Moon by 2020, by developing the Ares I Crew Launch Vehicle (CLV) propulsion elements now, with full extensibility to future Ares V Cargo Launch Vehicle (CaLV) lunar systems. This decision was reached after the Exploration Launch Projects Office performed a variety of risk analyses, commonality assessments, and trade studies. The Constellation Program selected the Pratt & Whitney Rocketdyne J-2X engine to power the Ares I Upper Stage Element and the Ares V Earth Departure Stage. This paper narrates the evolution of that decision; describes the performance capabilities expected of the J-2X design, including potential commonality challenges and opportunities between the Ares I and Ares V launch vehicles; and provides a current status of J-2X design, development, and hardware testing activities. This paper also explains how the J-2X engine effort mitigates risk by building on the Apollo Program and other lessons lived to deliver a human-rated engine that is on an aggressive development schedule, with its first demonstration flight in 2012.

I. Introduction – Overview of the Exploration Launch Projects Architecture

The U.S. Vision for Space Exploration requires safe and highly reliable launch vehicles to send astronauts to the Moon, Mars, and beyond.¹ The Ares I, slated to fly by 2014, and the Ares V, due to fly by 2020, are safe, reliable, sustainable space transportation systems built on a foundation of legacy knowledge and heritage hardware. Together, these systems will replace the Space Shuttle, which will be retired by 2010.

The Ares I and Ares V launch vehicles reduce risk by separating the Crew Exploration Vehicle's launch on Ares I from the Earth Departure Stage and Lunar Surface Access Module's launch on Ares V. The lunar mission begins by launching the Ares V Cargo Launch Vehicle, which carries the Earth Departure Stage and Lunar Surface Access Module into orbit. The Crew Exploration Vehicle (CEV) then launches on the Ares I, where it will rendezvous in orbit with the Earth Departure Stage.

Ares I, as shown in Figure 1, is a two-stage vehicle that will launch the Crew Exploration Vehicle into Earth orbit for missions to the International Space Station or to rendezvous with the Ares V for missions to the Moon, Mars, or other destinations. The Ares I first stage will be a single 5-segment Reusable Solid Rocket Booster (RSRB), which is derived from existing Space Shuttle hardware and uses polybutadiene acrylonitrile (PBAN) propellant. The Ares I upper stage is powered by the J-2X engine, a liquid hydrogen and liquid oxygen-powered engine derivative of the S-II and S-IVB upper stage propulsion used on NASA's Apollo Program Saturn V. The J-2X also will serve as the engine for the Ares V Earth Departure Stage.

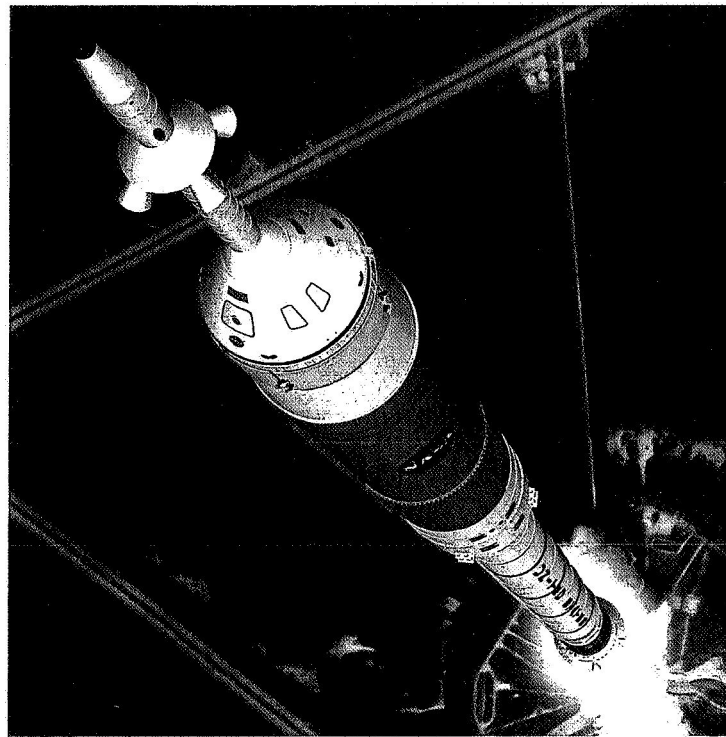


Figure 1. Ares I Crew Launch Vehicle concept.

The Ares V baseline configuration for lunar missions, depicted in Figure 2, consists of two Shuttle-derived 5-segment RSRBs, similar to the Ares I first stage, along with a 33-foot diameter tank delivering liquid oxygen/liquid hydrogen to a cluster of five RS-68 engines. This stack places the Earth Departure Stage and Lunar Surface Access Module into orbit. The second stage is the Earth Departure Stage, which is powered by a J-2X engine similar to the Ares I upper stage's engine. Once Ares V has reached orbit and docked with the Crew Exploration Vehicle, as depicted in Figure 3, the J-2X engine will initiate a trans-lunar injection (TLI) burn to reach lunar orbit. The engine hardware commonality is expected to reduce development and operations costs.

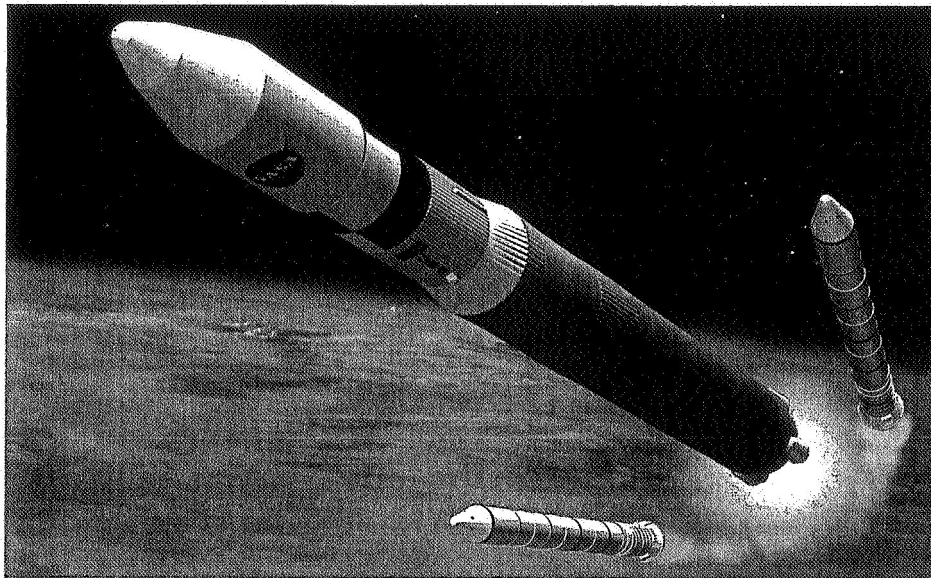


Figure 2. Ares V Cargo Launch Vehicle concept.

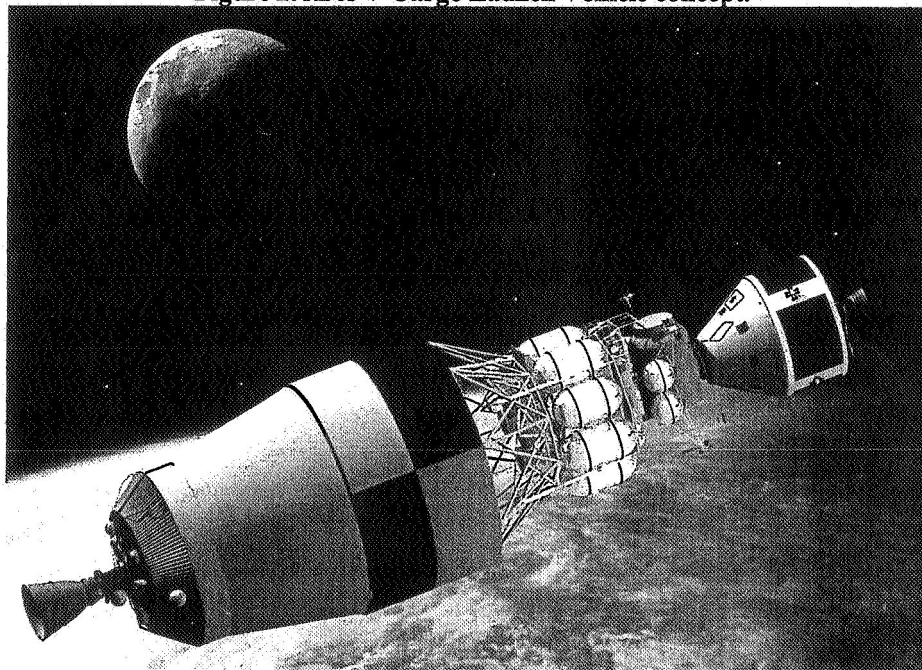


Figure 3. Earth Departure Stage and Crew Exploration Vehicle ready for trans-lunar injection burn.

II. Risk-Based Management Approach

It is well documented that propulsion is a high-risk area in developing any space vehicle mission, which is a risky endeavor in and of itself. NASA's risk reduction strategy for design, development, test, and evaluation of the J-2X engine is to build upon heritage hardware and apply valuable experience gained from past development efforts. For example, a key element of this engine, the turbomachinery, was successfully restarted during the X-33 Program. Understanding the results of that testing will inform the development cycle of the current design. In addition, NASA and its industry partner, Pratt & Whitney Rocketdyne, which built the original J-2, have tapped into their extensive databases and are applying lessons conveyed firsthand by Apollo-era veterans of America's first series of Moon missions in the 1960s and 1970s.

NASA's development approach for the J-2X engine includes:

- Early requirements definition and management.
- Designing-in lessons learned from the J-2 heritage programs.
- Initiating long-lead procurement items before the Preliminary Design Review.
- Incorporating design features for anticipated Earth Departure Stage requirements.
- Identifying facilities for sea-level and altitude testing.
- Starting ground support equipment and logistics planning at an early stage.

Other risk reduction strategies include using a proven gas generator cycle engine with recent development activity; using existing turbomachinery; applying current and recent advances in main combustion chamber and channel wall nozzle technology; and performing rigorous development, qualification, and certification testing of the engine system, with a philosophy of "test what you fly, and fly what you test." These and other active risk management strategies are in place to deliver the J-2X engine for low-Earth orbit and lunar return missions, as outlined in the U.S. Vision for Space Exploration.

III. Evolution of the J-2X Design Decision

The original Exploration Systems Architecture Study released in 2005 was charged with recommending and assessing viable launch system configurations for the Ares I and Ares V to support exploration of the Moon and Mars, as well as access to the International Space Station.²

As an integral part of the Exploration Launch Projects Office, the Upper Stage Engine Element team is to provide a propulsion system for both the Ares I Upper Stage and Ares V Earth Departure Stage. Three alternatives for the Ares I Upper Stage were considered during the Study: a single expendable version of the Space Shuttle Main Engine, a pair of J-2S engines—derivatives of the J-2 engine flown on the Saturn V launch vehicle's S-II and S-IVB stages—or a cluster of four new expander engines. The Study group preferred the Space Shuttle Main Engine (RS-25)—redesigned to be an expendable variant—for its long performance history and proposed commonality with the Ares V, which was going to use the Shuttle Main Engine on its Core Stage.³ The Earth Departure Stage would use two J-2S engines.

After the Exploration Systems Architecture Study, the second engine on the Earth Departure Stage was dropped due to weight constraints. It was also determined that the additional engine did not provide a comparable improvement in performance. The Exploration Launch Projects Office conducted a subsequent study in January 2006 to further evaluate the J-2 engine and its derivatives. The RS-68 was chosen as the main engine for the Ares V Core Stage following this extensive bottom-up review to dramatically reduce development and operational costs.

A. History of the J-2 Engine

The original J-2 engine was developed in the early 1960s for the Saturn IB and Saturn V vehicles. The liquid hydrogen engine, developed by Boeing's Rocketdyne division, was designed for high reliability, efficient packaging of components, and restart capability in flight.

Rocketdyne also developed a simplified version of the J-2, called the J-2S. The J-2S was also a liquid hydrogen engine with increased thrust and specific impulse, improved component accessibility, and the same vehicle interface as the J-2. The J-2S was a totally different engine from the J-2, in that it featured a unique tap-off cycle, where pressure is tapped off the main combustion chamber to drive the turbines, eliminating the need for a gas generator. While the tap-off cycle engine had its benefits, it also had design problems and was never flown. The engine study team was concerned because the J-2S was a new design with a low technology readiness level; additionally, it was untested and lacked complete drawings and documentation. In the end, the J-2S was not recommended as a viable option.

Two additional variations of the J-2S design—the J-2Sd and J-2+—also were considered as options for the engine study. The J-2Sd is a derived J-2S engine concept based on the J-2S tap-off cycle and existing J-2S Mk 29 fuel and oxidizer pumps. The J-2Sd engine design ultimately was not chosen for near-term development because its state-of-the-art thrust chamber assembly would have created schedule delays due to its low technology readiness levels; also, the engine would have been heavier than the original tube wall design. The J-2+ engine was used as part of the aerospike propulsion system designed for the X-33 Program and used existing Mk29 pumps and a new state-of-the-art injector, chamber, and nozzle, but it had the same potential schedule problems as the J-2Sd.

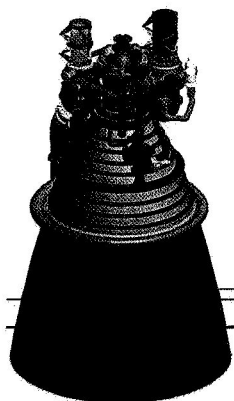


Figure 4. J-2X conceptual design.

Given the aforementioned limitations of other J-2 variants, the team selected the J-2X (Figure 4, at left), an advanced derivative of the J-2, as the engine for both the Upper Stage and the Earth Departure Stage. The J-2X will use gas generator cycle series turbines, with turbine exhaust gas going into the nozzle, and will produce more thrust than the original J-2. The engine will use J-2S turbopumps (Mark 29O and M29F) from the X-33, with the design being updated as needed to meet performance requirements and structural margins required by current NASA standards. The main combustion chamber has a copper liner with milled channels and a HIP-bonded jacket similar to methods used to design and fabricate the RS-68 engine.

The regeneratively cooled nozzle will have a 40-to-1 (40:1) expansion ratio and a milled channel wall. An uncooled nozzle extension will increase the expansion ratio from 40:1 to 80:1. The main injector contains coaxial elements similar to J-2 engine. The ignition system consists of an augmented spark igniter similar to the J-2 design, and incorporates improvements derived from the Space Shuttle Main Engine. The gas generator will use a J-2 design for the 274,000 pounds-of-thrust engine (which will be discussed later) and a Rocketdyne RS-68 engine design for the 294,000 pounds-of-thrust model.

The J-2X will use J-2 valve designs updated for current seal materials and structural requirements. Heritage actuators will be used where feasible, while most will be new or modified to incorporate current fault tolerance requirements. Finally, the J-2X will incorporate a new digital engine controller designed to meet fault tolerance and failure detection, isolation, and recover requirements. The system will use open-loop controls to ensure that the design is as simple as possible.

These attributes, developed through over 40 years of experience, will:

- Improve the J-2 engine's performance.
- Reduce the number of new engines to be developed.
- Take advantage of institutional NASA and industry knowledge regarding the J-2.
- Leverage a higher technology readiness level than was available for the Space Shuttle Main Engine.
- Simplify recurring operations.
- Reduce recurring and nonrecurring costs through fleet commonality.⁴

The J-2 engine also had an advantage in that it was a human-rated engine capable of restarting in flight, something the Space Shuttle Main Engine was not designed to do.⁵ Finally, the modifications needed to develop the J-2X were much less expensive and less risk-intensive than trying to modify the highly complex Space Shuttle Main Engine for in-flight restart.

IV. Engine Performance Expectations

By using the J-2X engine for both the Upper Stage Engine and Earth Departure Stage, the Exploration Launch Projects Office plans to provide a single-engine solution for the Ares I and Ares V upper stages. The Engine office plans to build one engine optimized for the lunar mission and make adjustments for each of the two upper stages, as necessary.

A. Commonality

The Commonality Assessment, conducted in May 2006, brought together a multi-disciplined panel of aerospace experts, some with Saturn and Shuttle experience, to assess potential synergy points and design challenges between the Ares I and Ares V vehicles.⁶ Driven by the upcoming Ares I System Requirements Review (SRR) and Ares V Initial Requirements Review (IRR), the panel was chartered to help determine which Ares V requirements might have the most impact on the desired commonality of hardware systems and components between it and the Ares I. Challenges and risks identified during this process resulted in follow-on analyses to support the Design Analysis Cycle, leading to the Ares I SRR in fall 2006.

The Commonality Assessment Report results are being used to perform advanced concept studies using the Vehicle Integrated Performance Analysis (VIPA) modeling and simulation capability and other systems engineering activities to further validate the baseline design configuration. The panel concluded that engine interfaces to the stage and main propulsion system should be the same for both vehicles. The processes for installing the engine into the stage could be made common as well, provided a common stage orientation is selected for both vehicles.

It might be possible to use common avionics and software components from the RS-68 engine on the J-2X. Common avionics and sensor components could be used on both launch vehicles by developing Ares I avionics and sensors that could be used on the Ares V.

The current belief is that one engine certification will cover the J-2X engine for both the Ares I and Ares V. However, while common standards can improve efficiencies and reduce costs in engine development, the differing natural environments and performance requirements for the two vehicles will result in very different engine specifications. Given the number of potential differences between Ares I and Ares V, a single qualification may not be sufficient.

The Exploration Launch Projects Office is gathering data on the potential impacts of the two engines' operational environments (acoustic, dynamic, and thermal) to determine the impact on commonality. Debris analysis and debris transport analysis also must be performed for the Earth Departure Stage/Core Stage separation sequence, along with material analyses of the Upper Stage Engine/Earth Departure Stage engine nozzle and other components.

B. Operational Environments

The Ares I Upper Stage Engine will be launched atop a single Reusable Solid Rocket Booster, ignite at altitude, and accelerate the Crew Exploration Vehicle or a cargo payload module to orbital velocity for rendezvous with International Space Station or the Ares V.

The Earth Departure Stage will launch one of three potential payloads: the Lunar Surface Access Module for lunar missions, cargo to orbit, or a potential single-launch solution to the Moon in which both the Crew Exploration Vehicle and Lunar Surface Access Module are carried aboard the Ares V at launch. As depicted in Figure 5, the Earth Departure Stage provides the final impulse to place itself and the Lunar Surface Access Module into a 160 nautical mile (nmi) (296 kilometer (km)) assembly orbit, and provides the impulse to accelerate the Crew Exploration Vehicle and Lunar Surface Access Module to escape velocity.

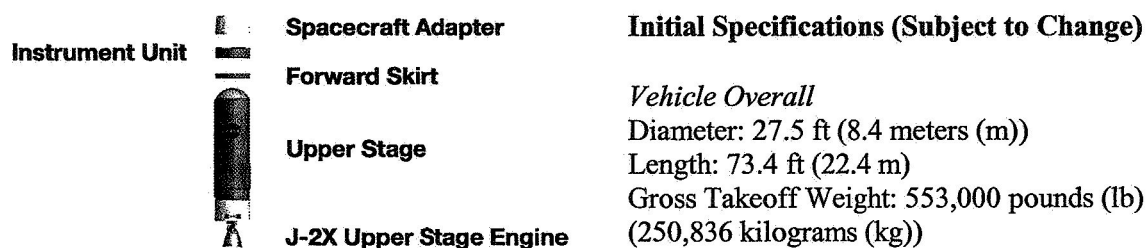


Figure 5. Ares I Upper Stage Configuration.



Figure 6. Ares V Earth Departure Stage configuration.

Orbital Velocity and Circularization Maneuver burn: 444.3 seconds
Orbit: 30 X 160 nmi (48 X 296 km)
Inclination: 28.5 degrees
Trans-lunar Injection burn: 324.1 seconds

The Earth Departure Stage is a conventional stage structure, containing one J-2X engine, a thrust structure/boattail, thrust vector control system, auxiliary propulsion system, and other stage subsystems. It is configured with an aft liquid oxygen tank comprised of forward and aft ellipsoidal domes. The liquid hydrogen tank is cylindrical with forward and aft ellipsoidal domes, and is connected to the liquid oxygen tank by an intertank structure. A forward skirt on the liquid hydrogen tank provides the attach structure for the lunar lander and payload shroud.

C. On-Orbit Loiter Requirement

The most stressing of the Earth Departure Stage's missions is the lunar launch scenario, as the current Constellation Architecture Requirements Document requires the vehicle to loiter in Earth orbit for up to 95 days. This window is necessary because the Earth Departure Stage and lunar lander are launched separately from the Crew Exploration Vehicle. This loiter time takes into account launch window availability, technical or weather delays, and other events that might delay the Crew Exploration Vehicle's rendezvous. However, this extended loiter period poses serious impacts to the Earth Departure Stage in multiple areas.⁷

The most significant design risks of the 95-day loiter requirement are related to on-orbit propellant management, which will require new technology to be developed. In addition, the Earth Departure Stage design must address the increased likelihood of micrometeoroid and debris impacts, which could pose a significant risk of vehicle mass growth, including a potential new design for the non-load-bearing propellant tanks, a new thermal protection system—both spray-on foam insulation and multi-layer insulation—and cryocoolers for on-orbit propellant management. At present, there are no known hydrogen flight cryocoolers. In general, because of its long stay in orbit, the J-2X on the Earth Departure Stage will face widely different thermal conditions from the engine used on the Ares I Upper Stage Engine.

The Earth Departure Stage will require additional flight instrumentation to monitor the condition of its various subsystems during the loiter period, including attitude sensors and hazardous gas detection systems, as well as additional software development and testing. All of these systems will require power for on-orbit operations and will result in additional vehicle mass, thus reducing payload capability. The Upper Stage Element team will employ NASA's systems engineering methodology to review and suggest tradeoffs to mitigate this problem.

D. Reaction Control

The delta-V required to perform the orbit circularization maneuver is on the order of 260 feet/second (79 m/s). Performing this maneuver using the J-2X requires approximately 6,500 lb of mass (2,948 kg) of propellant over a burn time of 9.9 seconds. However, this also requires using either the J-2X idle mode or an additional on-orbit start of the engine. Both the idle mode and an additional restart introduce unacceptable cost and risk to the J-2X, so an adjunct system would be required to perform the circularization burn. The net result is an increase in the Earth Departure Stage's mass with a corresponding loss of payload capability.

In addition, because the J-2X must be restarted to perform the trans-lunar injection maneuver, additional pressurizing gas (helium) will be required for propellant tank repressurization prior to initiating the burn.

E. Thermal Challenges

The Earth Departure Stage avionics suite, along with its power profile and thermal requirements, has not been defined yet. Some thermal control must be provided for the 95-day loiter period. This probably would include a combination of radiators, multilayer insulation, heaters, and possibly a pumped fluid loop, which would increase the complexity and weight of the design. Heat leaks also must be minimized within the Earth Departure Stage propellant tanks during the 95-day loiter period. Multi-layer insulation will be required to minimize boil-off, along with passive thermal control. The biggest technological challenge is that there is no heritage system for long-term, large-quantity cryogenic propulsion storage for use in orbit.

F. Two In-Flight Start Requirement

One of the most obvious differences in J-2X use between the Ares I Upper Stage Engine and Earth Departure Stage is the Earth Departure Stage's requirement for a second start for the trans-lunar injection burn. The Earth Departure Stage engine will have to perform two in-flight starts: a 490-second ascent burn to orbit and a 324-second trans-lunar injection burn.

The Earth Departure Stage engine will require additional solid propellant gas generators and igniters to initiate the second start. In addition, the engine will require active avionics and power during conditioning and terminal count for the second burn.

G. Commonality and Risk Management

While there are many potential differences between the Ares I Upper Stage Engine and the Ares V Earth Departure Stage engine, the J-2X is still the Engine office's design of choice because it is a proven, human-rated design in the correct thrust range and is capable of igniting in orbit. Despite the modifications that will need to be made to the J-2, it still has fewer design challenges than modifying the Space Shuttle Main Engine for this task.

V. Current Design and Development Status

The Exploration Launch Projects team has made significant progress since October 2005, when the effort to develop the launch vehicle began. The original recommendations by the Exploration Systems Architecture Study have been modified to provide more synergy between the vehicles, make them more cost effective, and make them available as soon as possible. The activities performed to date are summarized below. Most importantly, in less than a year the Exploration Launch Projects Office has assembled a team of experienced, capable professionals to develop the engine; identified the basic requirements of the engine; passed an important Preliminary Requirements Review (PRR); and begun testing on technology and hardware.

A. Establishing the Upper Stage Engine Team

The overall Constellation Program began with the initial Exploration Systems Architecture Study, released in November 2005. As stated earlier, the Exploration Launch Projects Office conducted a study in January 2006 to refine the new launch vehicle configuration, which resulted in selecting the J-2X. After the engine was selected, the Exploration Launch Projects Office set up an Upper Stage Engine Element Office to develop the J-2X. The assembled team draws upon experts in engine development from across NASA and its contractor partners, as well as consultants with direct experience with the Apollo Saturn program.

The Upper Stage Engine team's vision is to develop a single, highly reliable and affordable engine that satisfies the requirements for the Ares I Upper Stage Engine and the Ares V Earth Departure Stage Engine within the allocated schedule and budget. Its mission will be to minimize the gap in human space flight with a certified engine that is as simple as possible with only the required attributes, applying best practices and processes, and maintaining flexibility, where possible.

One of the first things the J-2X Upper Stage Engine Element Office did was reach back within the NASA and Pratt & Whitney Rocketdyne organizations to consult with individuals who had worked on the original J-2 engine. The Engine office formally chartered an independent team to provide assessments, ensure that the Engine office applied lessons learned, and verify that the team was "doing the right things." A J-2X "grey-beard" team (consisting of Apollo-era J-2 engineers) met to discuss historical problems with the engine and suggest possible design approaches for future engines. This independent team reported results based on previous data and participated in the J-2X Engine Preliminary Requirements Review (PRR).

The grey-beard team also contributed to NASA's risk reduction efforts by drawing upon their "lessons lived" during the Apollo era. Their inputs addressed a wide range of issues, including testing procedures, hardware evaluations, engineering fixes and problem-solving approaches, developmental lessons learned from the Space Shuttle Main Engine and Evolved Expendable Launch Vehicle programs, and potential design improvements for the J-2X.

Following the grey-beard discussions, the J-2X team developed a procurement strategy for the engine, as well as a draft statement of work. Based on the acquisition study, a bottom-up review was performed for the J-2X, which included: the engine's design and development approach; integrated master schedule with critical path assessments for immediate implementation; and project resource requirements (including labor, facilities, and budget). From these actions, the J-2X team was able to publish a synopsis of the engine to be developed, all within 4 months of engine selection. As the turbomachinery team continued its design and development work, the Engine office confirmed that the J-2X decision was the right choice for this effort.

B. Passing the Preliminary Requirements Review

As part of NASA's systems engineering process, the Ares I, Ares V, and all of their major elements must pass through a series of periodic reviews before moving on to the next stage of development. Prior to each review, the project or element offices must achieve specific milestones and prepare a specified list of data, design, and/or hardware deliverables. Those deliverables are reviewed and, if they are accepted, additional tasks are assigned and the project or element office can proceed to the next step in the development process. If not, further progress is put on hold until the project or element office completes the tasks assigned to it. For instance, before system design can begin formally, the vehicle's requirements must be reviewed. The J-2X engine has two milestone reviews for requirements-gathering verification and validation, the Preliminary Requirements Review (PRR) and System Requirements Review (SRR).

Between April and June 2006, the J-2X Office acted swiftly to create the planning and design documents necessary to take the next steps. These efforts included establishing the budget to support a first test flight in 2012; developing Data Requirements Documents; and completing a draft statement of work. The ultimate driving requirement for all of these efforts was to create a highly reliable engine with the lowest life-cycle cost.

In addition to planning documents, the Engine office also began making preliminary design decisions, though the engine description continues to evolve. For instance, the team reviewed the engine concept and utility analysis for defining and determining trades, as well as developmental planning. The team agreed that the gas generator should be used as a design solution to satisfy the program and project requirements. Also, the J-2X has been defined so that the thrust level requirements can be satisfied with minimal changes to the turbomachinery.

As an additional risk reduction measure, the J-2X office decided to develop two variants of the engine. The engines are designated J-2X and J-2XD, respectively. The “D” engine uses the same turbopumps as the J-2S variant described earlier and has a slightly lower (derated) thrust—274,000 pounds instead of 294,000 pounds—and a lower main combustion chamber pressure. The J-2XD is rated for low-Earth orbit operations; the 294,000 lb. J-2X is designed for lunar operations and is the primary engine design. The trade studies being performed will allow the team to develop a simple and potentially highly reliable and affordable engine. If the results from the initial testing of the J-2X are acceptable, the Engine team will stop working on the J-2XD and concentrate all of its efforts on the J-2X.

In May 2006, Exploration Launch Projects engineers on the Upper Stage Engine Board assessed entrance criteria for the Preliminary Requirements Review and determined that they were met. This process was completed in June, resulting in a requirements baseline. As a result of the Preliminary Requirements Review, the Engine office determined that the J-2X engine requirements were sufficient, correct, and mature enough to begin developing requirements for subsystems and components, as well as begin conceptual design of the engine and its components. Through the PRR process, the J-2X team determined that the engine was ready to proceed to the System Requirements Review in autumn 2006, which will verify that the engine’s requirements coincide with the needs of the overall launch vehicle.

C. Test Stand Facility Planning and Hardware Testing Activities

Because the J-2X is one of the highest-risk hardware items in the Constellation Program, it is crucial that the Engine office begins developing and testing the engine early. As depicted in Figure 7, testing and risk mitigation activities will occur during every step of the J-2X design and development process. The J-2X team already has made progress on testing the most important hardware components of the engine, including the gas generator, turbopumps, igniters, and injectors. Engine testing will occur in sea-level and vacuum environments, requiring the cooperation of several NASA Centers, including Marshall Space Flight Center in Alabama, Stennis Space Center (SSC) in Mississippi, and Glenn Research Center in Ohio.

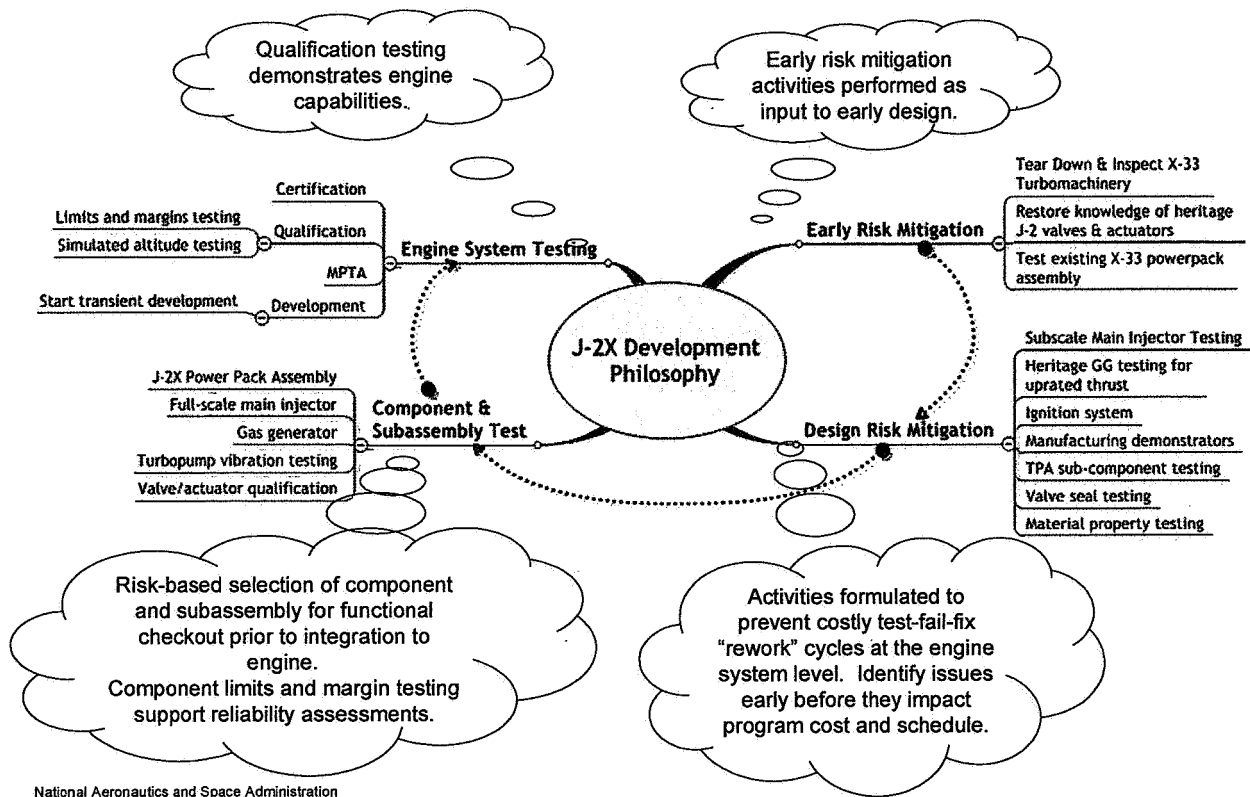


Figure 7. Upper Stage Engine Office incorporates risk mitigation throughout the J-2X development process.

The ability to ignite in-flight is a crucial and high-risk activity; therefore, the engine igniter and injector assemblies are among the first pieces of hardware the J-2X team is developing and testing. In April 2006 the J-2X team requested access to Test Stand A-1 at Stennis Space Center to perform critical testing of the power pack (gas generator and turbomachinery) and to prepare the stand for testing the engine system at sea level. The J-2X team also scheduled Marshall Test Stand 116 for risk reduction testing using subscale combustion devices; these tests will assess injector performance of candidate fuel injectors for the J-2X engine.

The Stennis A-1 Test Stand was dedicated to the J-2X team in June to accommodate early testing, though J-2X will share the Stennis facilities with the Space Shuttle Main Engine until October. Work continued to identify the other test stand at Stennis for acceptance and qualification testing, along with Glenn Research Center's Plum Brook facility for thermal and vacuum testing.

During May 2006, the J-2X team developed Facility Requirement Documents to support the required testing for the development, qualification, certification and acceptance testing for the J-2X engine. The J-2X will begin sea-level testing on Test Stand A-1 at Stennis Space Center in October 2006.

The J-2X heritage powerpack—consisting of the gas generator and the turbomachinery—will be used in a breadboard approach to begin testing the critical and highest risk turbomachinery and to prepare the test stand for J-2X operations. J-2X injector risk reduction testing began at Marshall during June, as well.

Because turbopumps and other machinery from the J-2 were used on the X-33's aerospike engine program, the J-2X team identified all of the existing assets required from the original J-2 and X-33 Programs and located them for transfer to the J-2X Engine Program. The X-33 turbomachinery was removed from the X-33 powerpack, which was located at Stennis and transferred to the J-2X group. Additional X-33 hardware was located at Marshall. The hardware was shipped to the contractor for tear-down and inspection. Figure 8 shows one of the turbopumps being removed from the X-33.



Figure 8. Turbomachinery being removed from the X-33 aerospike engine.

In June 2006, Marshall engineers completed testing of the J-2X augmented spark igniter, which will ignite the hydrogen and oxygen propellant elements in the combustion chamber. During the igniter tests, engineers integrated the igniter assembly—spark plugs, propellant injectors, and ignition torch—and fired it in a vacuum chamber. The tests simulated various levels of back-pressure exerted by gas molecules in the downstream preburner and main combustion chambers.

The tests replicated fluid conditions that the engine will experience when activated in low-earth orbit. However, the propellant components were at ambient, not cryogenic temperatures; future test propellants will be chilled to -260 °F prior to injection. Test data showed that the test igniter performed properly under ground-start conditions. Initial assumptions concerning its operation at simulated altitude or low back pressure conditions have also been verified. The test data will be combined with computer models to develop a comprehensive understanding of how to ensure that the igniter operates safely and reliably.

Marshall personnel also completed hot-fire testing of a subscale main injector, which injects and mixes liquid hydrogen and liquid oxygen in the combustion chamber, where they are ignited to produce thrust. The subscale injector contained 40 individual propellant flow elements (Figure 9). Approximately 50 hot-fire tests are planned for the series, with the goal of ensuring repeatability and reliability.



Figure 9. Subscale main injector test.

Subscale testing of the injector resumed in July. This portion of the test series tested the 58-element injector, which is the J-2X baseline element density, at the same conditions used for the previously tested 40-element injector. The J-2X Combustion Devices Integrated Product Team went to 100% power level on the planned injector design. This test was performed at Marshall Space Flight Center's East Test Area. The injector design was a 58-element shear co-axial design and produced approximately 20,000 pounds of thrust. The preliminary results indicate that the efficiency is near the expected values and will help the Engine office anchor the combustion models and select the injector design to assure that performance objectives are satisfied over the operating range of flight conditions. Comparisons were made to assess the potential performance gains by increasing the injector element density. This data will be applied toward the design and manufacture of a full-scale injector design, which will be tested in 2007. The engine test team at Stennis has developed a concept of operations for proceeding with the test program.

D. Upcoming Milestones

While the J-2X Upper Stage Engine team has made much progress, there is still much to be done to be ready the engine for its first flight. For instance, the Engine office plans to build and test nearly a dozen development engines between now and 2012. Other project milestones appear in Table 1 below.

Table 1. J-2X engine upcoming development milestones.

Time	Event
October/November 2006	Upper Stage Element System Requirements Review and System Design Review completed
October 2006	Contractor Systems Design Review Integrated Baseline Review NASA-led System Requirements Review Presentation
November 2006	NASA-led System Requirements Review Board
December 2006	Acceptance Test Plan for design, development, test, and evaluation completed Design, Development, Test & Evaluation contract awarded
Spring 2007	Powerpack testing begins at Stennis Space Center Test Stand A-1
May 2007	NASA-led Preliminary Design Review
May – October 2007	Gas Generator “Work Horse” Testing Begins
May 2008	Critical Design Review
May 2010 (or ASAP)	First J-2X Engine Systems Test (“Green Run”)
December 2010	Main Propulsion Test Article built
March 2012	Design Certification Review

VI. Conclusion

NASA’s Exploration Launch Projects Office is dedicated to designing the Ares I and Ares V launch vehicle systems for safety, simplicity, robust operability, and streamlined supportability to reduce operations costs, allowing NASA’s resources to be focused more fully on space exploration instead of routine operations. The Exploration Launch Projects Office will continue to reduce risks by drawing upon lessons learned in the past and applying modern engineering tools and processes. Hardware commonality between the two launch vehicles—as exemplified by the J-2X engine element—will reduce the fleet’s logistics footprint, as well as nonrecurring and fixed operations costs. The J-2X team will continue to emphasize a “test as you fly, fly what you test” development philosophy as it begins testing critical engine hardware. This team-based, test-based engineering strategy will help sustain long-term space exploration, expanding humanity’s reach to the Moon, Mars, and beyond.

References

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- ⁷ Ibid.